

Collider searches for non-perturbative low-scale gravity states

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Abstract The possibility of producing non-perturbative low-scale gravity states in collider experiments was first discussed in about 1998. The ATLAS and CMS experiments have searched for non-perturbative low-scale gravity states using the Large Hadron Collider (LHC) with a proton–proton centre of mass energy of 8 TeV. These experiments have now seriously confronted the possibility of producing non-perturbative low-scale gravity states which were proposed over 17 years ago. I will summarise the results of the searches, give a personal view of what they mean, and make some predictions for 13 TeV centre of mass energy. I will also discuss early ATLAS 13 TeV centre of mass energy results.

Keywords: black holes, extra dimensions, beyond Standard Model

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1 Introduction

Brane world scenarios [1, 2, 3] offer paradigms to reinterpret the four-dimensional Planck scale M_P as an effective gravity scale arising from a more fundamental lower gravity scale M_* in higher dimensions. This reinterpretation of the gravity scale allows new phenomenological models [4, 5] to be developed which help guide searches for low-scale gravity in experiments, such as those at the Large Hadron Collider (LHC). An exciting outcome of these models is the possibility to produce non-perturbative gravity states at the LHC. The ATLAS and CMS experiments have recently published a round of searches at 8 TeV proton–proton centre of mass energy for non-perturbative gravity states which seriously confront the models for the first time. I examine how the models can now be viewed in light of the experimental constraints.

2 Non-perturbative gravity states

Before we begin, I discuss how including non-perturbative gravity into particle physics can perhaps involve a slight modification to the usual thinking. The way of thinking is slightly different from main-stream particle physics. Particle physicists are use to searching for new particles. They need quantum mechanics and special relativity to described them. For calculations, they usually have a Lagrangian in field theory, and use perturbative techniques to expand the result in a series of Feynman diagrams. States with energy above the gravity scale (transplanckian scale physics) are described non-perturbatively. Classical or semi-classical mechanics should hold. Being non-perturbative, expansions in a coupling constant and Feynman diagrams do not make much sense.

Like searches for new particles, we usually think of one force – in this case gravity – dominating the interaction and ignore the others – in this case QCD – so many QCD issues (LO, NLO, NNLO, etc.) are not relevant for non-perturbative gravity states.

Several paradigms for model development exist. I refer to them as paradigms as they are not specific models but frameworks which allow models to be developed. Two extra dimensional scenarios are the most popular: large flat extra dimensions proposed by Arkani-Hammed, Dimopoulos, Dvali (ADD) [1, 2], and a warped extra dimension in AdS space proposed by Randall and Sundrum (RS1) [3]. Universal extra dimensions are also popular but not relevant to the phenomenology discussed here. An alternative approach to using extra dimensions to lower the Planck sale is due to Dvali, in which a large number of particle species (messenger particles) are proposed [6]. In general, one needs some idea to reduce the Planck scale M_P to a lower gravity scale M_* , such that $M_P \gg M_*$. I will use M_D for M_* from now on, although the definition of the scale is model dependent.

Many ideas describing the effects of low-scale gravity exist but few of them allow a concrete model to be developed and utilised by experiments to perform a search for low-scale gravity phenomena. The most popular model describes higher-dimensional black holes using the theory of general relativity. This model treats the production of black holes in particle collisions classical, and the decay is teated using the semi-classical physics of Hawking

evaporation [7]. Throughout this review, I will refer to these types of black holes models as general relativistic (GR) black holes.

Since string theory, such as superstrings, occurs in higher dimensions, it is natural to attempt to embed string theory into ADD. In the regime of weakly-couple string theory, the correspondence between black holes and string states manifests itself in terms of a highly-excited string state, or string ball [8]. I will refer to string balls together with GR black holes, as thermal black holes.

The above two models consider the non-perturbative objects as thermal states. It is believed in the quantum gravity regime the transplanckian gravity state will behave more like a particle, and decay non-thermally [9]. These non-thermal black holes are often called quantum black holes or QBH. I will refer to them as non-thermal black holes.

A few other less popular models have been discussed in the context of having different phenomenology to the above at the LHC. Attempts to calculate the gravity cross section of two colliding particles (trapped-surface calculations) allows alternative levels for black hole production [10]. The early concept of fermions residing on separate branes [11], split-fermions, makes concrete predictions and can be used in model building. ADD has been embedded into a non-commutative geometry [12] in hopes to better model the effects of quantum gravity.

A model is of little use to an experiment unless it can be implemented in a Monte Carlo event generator. One such generator is **CHARYBDIS2** [13] which simulates GR black holes. String balls have been added [14], and the code modified for non-commutative black holes [15]. The **BlackMax** generator [16] also simulates GR black holes, has had string balls added [14], and is capable of simulating split-fermion models. The **QBH** generator is most often used for simulating non-thermal black holes [17].

To discuss searches for non-perturbative gravity states, we need to first access the current bounds on the parameters of the models. I will restrict this discussion to ADD. No bounds exist on the number of extra dimensions besides that one large flat extra dimension is not consistent with our daily observations. The parameter of interest is the fundamental Planck scale M_D and I will ask what the limits on this parameter are from existing experimental measurements. An up to date summary can be found in Ref. [18]. Searches for virtual graviton emission depend on an ultra-violet cutoff M_s , which is not M_D . Real graviton emission depends on M_D . The most stringent limits come from searches for mono-jet events and mono-photon events. But is this the scale for thermal and non-thermal black holes? I argue that this is the case when the search is interpreted in terms of the ADD model, i.e. the same model that is predicting the non-perturbative gravity states. Direct searches for non-perturbative gravity states do not allow very stringent limits on the fundamental Planck scale. Limits on thermal states are given in terms of M_D as function of M_{th} , a mass threshold. Since M_{th} is not a physical parameter, it is not possible to infer much about M_D from these searches. Limits from non-thermal black hole searches can assume $M_D = M_{th}$, where a limit is set on the later quantity. Since this assumption is only approximately valid, limits on M_{th} are not valid statistical limits on M_D . In the following discussions, I will use the most stringent limits of $(n, M_D) = (2, 5.61 \text{ TeV}), (3, 4.38 \text{ TeV}), (4, 3.86 \text{ TeV}), (5, 3.55 \text{ TeV})$, and

(6, 3.26 TeV) from the CMS mono-jet search results [19].

3 Searches for non-perturbative gravity states

Only the LHC experiments ATLAS and CMS have performed searches for non-perturbative gravity states. In the discussion of these results, I will divide the searches into thermal and non-thermal gravity states. For each experiment, I consider only the most recently published paper using a particular analysis strategy. These sometimes supersede previous publications which used data at lower energy or lower luminosity, or results found in LHC public conference notes.

Thermal gravity states such as GR black holes and string balls have been searched for by ATLAS [20] and CMS [21, 22, 23] in multi-jet events. In addition, ATLAS has searched for the same states in ℓ +jets events [24, 25], and same-sign dimuon events with a large number of tracks [26, 27].

Non-thermal black holes have been searched for by ATLAS [28] and CMS [29, 22, 23, 30] in dijet events. In addition, ATLAS has searched in γ +jets events [31], ℓ +jets events [32], and dilepton events [33] for non-thermal black holes. In all cases, I refer to a lepton as either an electron or a muon only. ATLAS has also searched in dijet events for thermal black holes extrapolated down to the Planck scale [34, 35, 28].

3.1 Searches for GR black holes

The key feature of GR black holes is that they are thermal states which Hawking evaporate. The evaporation is a semi-classical description and the production mechanism is described classically. However, since low-scale gravity is expected to require a quantum mechanical description, we need to introduce a cut-off parameter M_{th} and impose the condition $E > M_{\text{th}} \gg M_D$ for the GR black hole models to be valid. Thus these states offer no predictive power of what we would see first at lower energies ($E < M_{\text{th}}$) at the LHC if low-scale gravity is realised. For first signs of low-scale gravity, it is best to look for perturbative states, such as Kaluza-Klein resonances, graviton scattering, etc.

Thermal decays are anticipated to give rise to mostly partons, which will then hadronise and create jets. Thus a search in events with a high multiplicity of high- p_T jets (or particles) is a good choice for detecting thermal black holes. In this type of search, the QCD background can be high, but can be reduced by requiring a high- p_T lepton in the event. A significant fraction of leptons should occur in high-multiplicity thermal decays. In these searches a non-physical mass threshold M_{th} is introduced to keep the black hole classical. As we shall see, the criteria of $M_{\text{th}} \gg M_D$ is seldom obeyed in the stated experimental limits, and hence the results are of limited use in constraining these model. This was also pointed out by Park [36].

Model-dependent limits have been set in multi-jet searches by ATLAS [20] and CMS [21, 22, 23], and in ℓ +jets [24, 25] and dimuon [26, 27] searches in ATLAS. The models used are given by rather standard configurations of the CHARYBDIS2 and BlackMax generators. A

two-dimensional parameter space in M_D and M_{th} is used, thus giving 95% confidence level (CL) contour limits on these parameters. I remind the reader that M_{th} is not a physical parameter of the model. The region in the bottom left of the plots (low M_D and low M_{th}) is excluded. These limits are obtained by assuming the model production cross sections to have no uncertainty. Sometimes uncertainties in the parton density functions are taken into account in the efficiency calculation. Since black hole cross sections are highly speculative these limits can only represent limits on some assumed model for the cross section, and should not be considered limits on new fundamental physics.

Limits on M_{th} are set for a series of M_D values. The M_D values range from 1.5 TeV to 4.5 TeV in CMS and 1.5 TeV to 4.0 TeV in ATLAS. The lower bound of 1.5 TeV seems rather low when considering the limits on M_D from searches for graviton emission, and all the other exotics and SUSY searches performed at the LHC, which have not seen any hint for new physics, let alone, a new physics scale. The upper bound on M_D seems rather arbitrary. Perhaps the reason to not go higher has been to avoid a region in which the models are not valid, but I will argue below that the models are unlikely to be valid in any region of these contours. Park [36] has expressed similar concerns four years ago.

Figure 1 shows a schematic of the model-dependent limit validity region. For a given value of n , limit contours are set in (M_{th}, M_D) . Based on existing lower limits on M_D , the region to the left of the $M_D(\text{limit})$ vertical line is excluded. A metric for the validity of classical models is often given as $M_{\text{th}} \gg M_D$, or $k \equiv M_{\text{th}}/M_D \gg 1$. Clearly this is not the case in the published contour limits. A popular value for validity in the literature is $k > 5$, which is also questionable. This results in a region of validity to the left of the $k = 5$ line in Fig. 1. The allowed region is thus $M_{\text{th}} > 16$ TeV, which is currently beyond the LHC energy reach. In summary, the model-dependent limits to date are not particularly relevant to constraining low-scale gravity physics.

The limits can provide some comparisons between models, analysis procedures, and differences between experiments. The limits on M_{th} are typically highest at low M_D and decrease monotonically with increasing M_D . Comparing the multi-jet analyses to the ℓ +jets analysis you can see that the lower efficiency for ℓ +jets is dominating over the reduction in QCD background to give slightly less stringent limits. You can also see that the ℓ +jets limits are more dependent on rotation and decrease faster as M_D increases. This is related to the requirement of a high- p_T fermion in the final state. The multi-jet analysis of both ATLAS and CMS are comparable. The small differences can be attributed to the small luminosity difference and the inclusion of missing transverse momentum by CMS.

I use the following procedure when discussing the mass limits. The cross section limits are interpret with models that are generally a function of (n, M_{th}, M_D) . n is a fundamental parameter of the brane-world and can only have one value. Limits have been set for $n = 1 - 6$ (CMS), but ATLAS considers only $n = 2$ and 6, at most. We have no information for larger n , and possibilities are not ruled out in non-string theory models. Limits on M_D for different n have been obtained [19]. I invoke these limits as a condition to reduce the (M_{th}, M_D) limit space. This gives limits on M_{th} for different n . I also note the k value and suggest that it be reasonable for the model used.

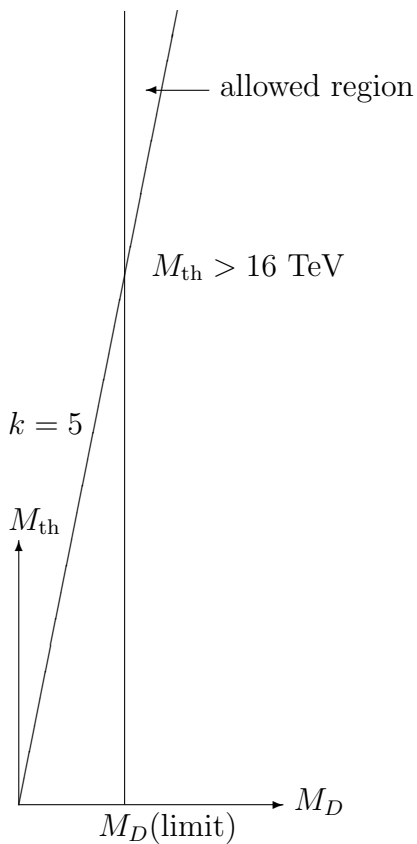


Figure 1: GR black hole search parameter space. The valid region is to the right of the vertical $M_D(\text{limit})$ line and to the left of the $k = 5$ line.

All searches for GR black holes have set model-dependent limits. However, recent results from ATLAS using 80 pb^{-1} of data with the LHC running at 13 TeV centre of mass energy have set the the most stringent limits. A multi-jet analysis [37] obtains $M_{\text{th}} > 8.5 - 7.5 \text{ TeV}$ for $M_D = 2 - 5 \text{ TeV}$ ($k = 4.2 - 1.5$) at the 95% CL. Invoking the current limits on M_D gives $M_{\text{th}} > 8.1 \text{ TeV}$ ($k = 2.5$). Similarly, a ℓ +jets analysis [38] obtains $M_{\text{th}} > 7.3 - 5.9 \text{ TeV}$ for $M_D = 2 - 4 \text{ TeV}$ ($k = 3.6 - 1.5$) at the 95% CL. Invoking the current limits on M_D gives $M_{\text{th}} > 6.4 \text{ TeV}$ ($k = 2$). While these are significant improvements over the mass threshold limits at 8 TeV proton-proton centre of mass energy, they are still not in a region of parameter space in which the models are particularly valid.

3.2 Searches for string balls

Embedding weakly-coupled string theory into ADD results in string ball states that could be searched for at the LHC [8]. The model [14] modifies the black hole cross section, but

leaves the decay mechanism similar to thermal black holes – except the temperature is different. String ball models are expected to be valid at lower values of energy than the GR models. This is accomplished by introducing another scale (the string scale M_s) that allows $E > M_{\text{th}} \gg M_s$ and $M_D > M_s$. In reality, this just pushes the validity of GR black holes to lower energy at the expense of more speculation (low-scale string theory).

Similar to GR black holes, model-dependent limits have been set for string balls. String balls have the additional parameters of the string scale and string coupling. However, when also considering the Planck scale, only two of the three parameters are independent. The experiments have chosen to take M_s and g_s as the independent parameters. g_s is fixed as part of the model, and M_s replaces M_D . M_D is not independent and is calculated. The contours are thus in M_{th} and M_s space. M_s ranges from 0.8 TeV to 3.0 TeV in ATLAS. Although there have not yet been any direct limits on M_s it is hard to imagine from the many searches that have been performed at the LHC that they have not ruled out values as low as 0.8 TeV. The upper search bound on M_s seems arbitrary. A requirement of $k = M_{\text{th}}/M_s \gg 1$ is also necessary for validity of the model. This ratio could perhaps be lower than for the case of GR black holes. A common choice is $k > 3$, and this is satisfied in a region of the search space. However, this is a region in which M_s is low, so the valid region exists where string physics has probably been excluded, and the region of allowed M_s is in an invalid region of the model. In this regards, these limit contours are also of limited use for constraining low-scale gravity. Perhaps at higher LHC energy the limits will constrain the model. When setting limits on string-ball models it is important to choose the parameters such that the stringy-regime of the cross section is in the region where the limits are set, else one is effectively setting limits on GR black holes.

String balls have been searched for in the multi-jet and ℓ +jets final states. Both ATLAS and CMS set limits using a model in which $g_s = 0.4$. The most stringent limits on string balls come from the multi-jet searches. Taking rotating string balls as an example, the ATLAS limits [20] on (M_{th}, M_s) range from about (6.35 TeV, 0.8 TeV) ($k = 7.9$) to about (4.9 TeV, 3.0 TeV) ($k = 1.6$) at the 95% CL. For $k = 3$, the lower limit is (5.35 TeV, 1.8 TeV). CMS obtain similar limits [23]. The limits from the ATLAS search in the ℓ +jets final state are less stringent [25].

3.3 Model-independent limits

The lack of discovery in signal regions allow upper limits to be set on the number of signal events N_{upper} , which is independent of model assumptions. These limits can then be used for any new physics model that has the same signature as that used in the search. These upper limits on events allow a determination on the upper limit of cross section $\sigma_{\text{upper}}^{\text{vis}}$ times branching fraction B times efficiency ε times acceptance A :

$$N_{\text{upper}} = \sigma_{\text{upper}}^{\text{vis}} L A \varepsilon, \quad (1)$$

where L is the integrated proton–proton luminosity, which is typically about 20 fb^{−1} in the analysis discussed here. This is often referred to as the visible cross section. Thermal

black hole searches are usually made using inclusive final states so the branching fraction is included in the efficiency.

The cross section limits are presented as a function of a search variable which is usually the scalar sum of the transverse momentum of all the particles in the event $\sum p_T$. For the multi-jet searches this is referred to as H_T . This variable is often used inclusively, and the signal regions can also be sliced in inclusive particle multiplicity. Figure 2 shows a schematic of the model-independent limit. Just knowing where in $\sum p_T$ the limit has a lower plateau is useful. This represents the highest $\sum p_T$ value of all the events. This then becomes a conservative and model-independent limit on $\sum p_T$, or whatever variable is used. Beyond this value of $\sum p_T$ there are no data events at higher $\sum p_T$ and a negligible background in this region is predicted. The plateau represents the highest excluded cross section, given by an upper limit of three events, above the highest $\sum p_T$ data event.

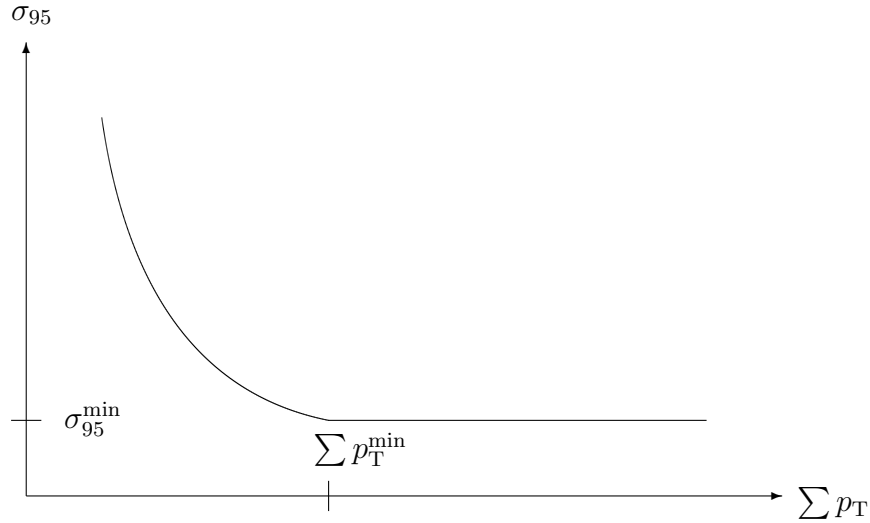


Figure 2: Schematic of the 95% confidence level cross-section upper limit versus $\sum p_T$ (model-independent limit).

To set upper limits on the cross section requires the experiments to provide the acceptance time efficiency. To allow different models to be confronted, the acceptance is usually not given, but is meant to be determined for the model of interest, usually by Monte Carlo generator methods. It is useful to make a clear distinction between the detector and geometrical effects. The efficiency on the other hand can only be determined by the experiment. In all but the simplest cases, this efficiency will depend on the model considered. In this way the model-independent limits are not really model independent.

Sometime no efficiency is given, if the search is likely to be close to fully efficient. Sometimes the lowest efficiency is given, to be conservative, and will probably allow estimates

to a factor of a few. Sometimes a mean and spread of efficiencies are given, or a set of efficiencies. One can then match the model of interest to the closest model for which the efficiency is given. Since models for non-perturbative gravity states are highly speculative and uncertain, it should be sufficient to just take the detector efficiency to be unity, and make an approximation of the acceptance. In this way, the visible cross section is totally adequate for model builders to determine if their model has already been ruled out by existing LHC experimental limits.

The most stringent upper limits on the visible cross section are about 0.2 fb at the 95% CL from the ATLAS multi-jet search [20]. This should be valid for most new phenomena resulting in high- p_T and high multiplicity jet final states. As a consequence, searches in run-2 at the LHC should not need to be concerned about signal contamination in the background estimate until the data sample reaches a luminosity of about 15 fb⁻¹.

For classical black holes, the independent variable has been $\sum p_T$. Unfortunately, this variable is not related to analytical expressions for the proton–proton or parton–parton cross sections. Cross sections are usually given as a function of black hole mass M , or the parton–parton centre of mass energy $\sqrt{\hat{s}}$. There is no one-to-one relationship between $\sum p_T$ and M . A transformation of $\sum p_T$ to M will involve assumptions (model) of the distribution of these variable, and unless the transformations are done carefully, the result will not be a rigorous 95% CL limit as a function of M . However, since $\sum p_T < M$ for well measured events, a limit in $\sum p_T$ is a conservative limit in M . Exactly how conservative can only be approximated. Removing the model-dependency and expressing the limit in M would be a great step forward.

3.4 Searches for non-thermal black holes

The LHC parton–parton centre of mass energy needs to be high relative to M_D for a black hole to Hawking evaporate thermally – so black holes produced with a mass near M_D probably do not decay thermally but decay more like a particle. In the later case, considering a non-thermal black hole model [39, 40] is probably more appropriate [9]. Models for non-thermal black holes extrapolate the classical cross section down to the Planck scale. More importantly, most models replace Hawking evaporation (thermal decay) by particle decays. The branching fractions can be approximated by invoking conservation principles. The ATLAS and CMS experiments have searched for non-thermal black holes in a variety of two-body final states.

3.4.1 Searches in the dijet final state

Because gravity is expected to couple to all standard model particle degrees of freedom equally, it is anticipated that the final states involving quarks and gluons will dominate. All 14 QBH states considered in Ref. [39, 40] will have a significant probability to decay to partons. Such final states will lead to hadronic jets in the LHC detectors. Searching for new phenomenon in the dijet invariant mass spectrum is a powerful approach to searching for non-thermal black holes.

Some of the first searches for new particles in the LHC experiments interpreted the lack of a signal in terms of production limits on QBH states. For CMS, the dijet signatures of QBH were initially included with the thermal black hole searches [29, 22] but the latest results were published [23, 30] along with the search for narrow resonances in the dijet invariant mass spectrum. CMS interpret the non-observation of a broad enhancement in the dijet invariant mass spectrum as lower limits on the QBH mass of 5.0 to 6.3 TeV at the 95% CL. In obtaining this mass range, CMS consider $M_{\text{th}} > M_D$ and take $M_D = 2 - 5$ TeV and $n = 1 - 6$. The limits range from about (M_{th}, M_D) of (6.3 TeV, 2.0 TeV) ($k = 3.2$) to about (5.2 TeV, 5.0 TeV) ($k = 1.0$) for $n = 6$ to $n = 2$ at the 95% CL, respectively. Invoking the current limits on M_D give limits of $M_{\text{th}} > 5.6 - 6.05$ TeV ($k = 1.4 - 1.9$) for $n = 3 - 6$ at the 95% CL. This is the region in which the QBH model is expected to be valid. The limits obtained for $n = 2$ are not compatible with existing limits on M_D . The higher the k , the higher the limit on M_{th} – although the highest k may not be that chosen by nature. The $n = 1$ case has its cross section modified to correspond to the RS1 model, and the limits are (5.7 TeV, 2.0 TeV) to (5.0 TeV, 4.0 TeV) at the 95% CL. Upper limits on $\sigma \times B \times A$ at the 95% CL of about 0.2 fb^{-1} are obtained.

ATLAS has only recently interpreted the dijet invariant mass spectrum in terms of non-thermal black holes [28]. Prior to this [34, 35], and in Ref. [28], the interpretation has been in terms of a model that performs two-body Hawking evaporation at the Planck scale [16]. In such a model, the conservation principles followed in Ref. [39, 40] need not be obeyed simultaneously. I consider this model as essentially the classical thermal black hole model at the Planck scale. Since this is the energy at which a classical model is anticipated not to be valid, and the black hole must be treated as quantum mechanical particle, I will not consider the model presented in Ref. [16] further.

ATLAS interprets the non-observation of a broad enhancement in the dijet invariant mass spectrum as a lower limit on the QBH mass of 5.66 TeV at the 95% CL for $M_{\text{th}} = M_D$ and $n = 6$ [28]. Upper limits on the $\sigma \times A$ at the 95% CL of about 0.2 fb are obtained above a mass of about 5 TeV. Recent results from ATLAS [41] using 80 pb^{-1} of data with the LHC running at 13 TeV centre of mass energy have significantly improved the lower mass limit to 6.8 TeV.

3.4.2 Searches in the photon and jets final state

A similar search to dijets for QBH states can be performed in the photon and jet invariant mass spectrum. Since the photon is an electrically neutral vector particle, $QBH \rightarrow \gamma + \text{parton}$ decays are not allowed for all possible initial parton-parton states. Possible initial states are $q + g$, $\bar{q} + g$, $q + \bar{q}$, and $g + g$. The $u + g$ state dominates. The $\gamma + \text{parton}$ final state should appear in detectors as a $\gamma + \text{jet}$ invariant mass enhancement. To date, only one search by ATLAS has been performed [31]. The signal model has been converted to a visible cross section and a lower mass limit of 4.6 TeV at the 95% CL has been obtained. 95% CL upper limits on the visible cross section are obtained. The visible cross section has a minimum of about 0.5 fb starting at a mass of 3 TeV.

3.4.3 Searches in the lepton and jets final state

Strongly coupled gravity need not conserve global symmetries such as baryon or lepton number. The $q + q$, $\bar{q} + \bar{q}$, $q + q'$, and $\bar{q} + \bar{q}'$ states can produced $QBH \rightarrow \ell + q$, where ℓ is a charged lepton, and q is a quark or antiquark. A gluon is not possible due to simultaneous conservation of total angular momentum and electric charge. This decay should appear in detectors as a lepton and jets. Only ATLAS has performed a search [32] by looking for an enhancement in the ℓ +jet invariant mass spectrum, where ℓ is an electron or a muon. The signal model has been converted to a visible cross section and a lower mass limit of 5.3 TeV at the 95% CL obtained. The 95% CL upper limit on the $\sigma \times B$ is about 0.18 fb above a mass of about 3.5 TeV.

3.4.4 Searches in the dilepton final state

Electrically neutral QBH states formed in $q + \bar{q}$ and $g + g$ collisions can decay to opposite signed dileptons. Only one search by ATLAS [33] has been performed by looking in the dielectron and dimuon invariant mass spectra. 95% CL upper limits on the $\sigma \times B$ are obtained. The signal model has been converted to $\sigma \times B$ and a combined lower mass limit at the 95% CL of 3.65 TeV for an ADD model and 2.24 TeV for an RS1 model have been obtained. The $\sigma \times B$ at the 95% CL is below about 0.5 fb above a mass of about 2 TeV.

3.4.5 QBH search summary

Searches for QBH states in the dijet, γ +jets, ℓ +jets, and dilepton invariant mass spectra have been performed. No enhancements have been observed and limits have been set on the production cross section for these final states. The cross section limits have been interpret in terms of lower limits on the threshold mass. All of the ATLAS searches have set lower mass limits using an identical model and can be directly compared, as shown in the second column of Table 1. We see that the dijet limits are the highest in spite of the large QCD background. The limits are restricted to the case $M_{\text{th}} = M_D$ and $n = 6$.

Final state	$M_{\text{th}}[\text{TeV}]$	
	$\sqrt{s} = 8 \text{ TeV}$	$\sqrt{s} = 13 \text{ TeV}$
jet + jet	5.7	8.5
$\ell + \text{jet}$	5.3	7.5
$\gamma + \text{jet}$	4.6	6.5
$\ell^+ + \ell^-$	3.6	5.0

Table 1: 95% CL lower limits on the QBH threshold mass for different final states in the ATLAS detector. The 8 TeV column corresponds to published results, while the 13 TeV column are approximate predictions for 3 fb⁻¹ of data.

The upper limits on $\sigma \times B$ can be compared as a function of the two-object invariant mass. This is shown in Fig. 3(left). However, the branching fractions are different for each

final state and hence the limits can not be directly compared. The same model used to set the limits can be used to estimate the branching fractions. Figure 3(right) shows the combined limits on the production cross section for QBH decaying to two objects. Clearly, the dijet search provides the lowest cross section and highest mass limits.

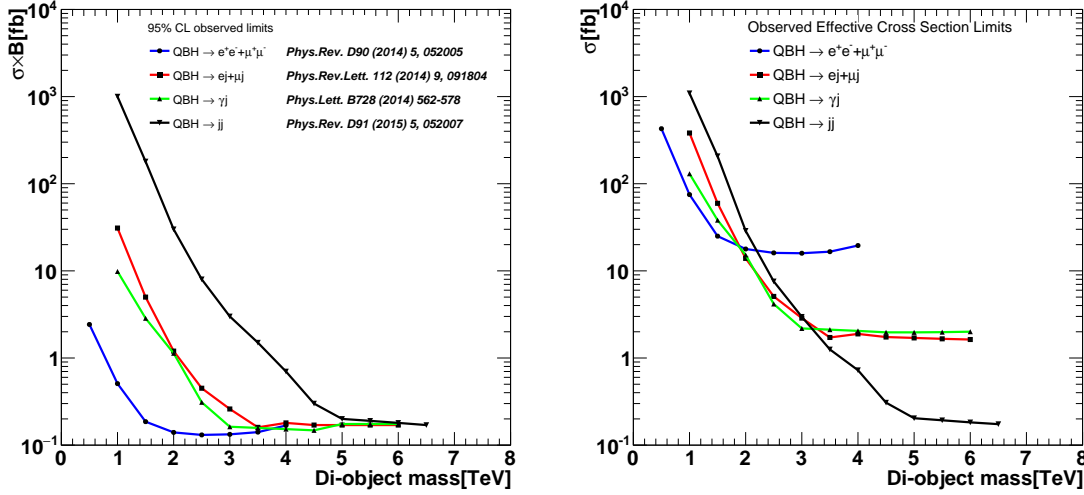


Figure 3: ATLAS upper limits on (left) $\sigma \times B$ and (right) σ at the 95% CL for QBH production in different final states.

Figure 4 shows the QBH production cross section time branching fraction for proton–proton centre of mass energies of 8 TeV and 13 TeV. Significant mass sensitivity increases can be expected and are estimated for 3 fb^{-1} of data in the last column of Table 1.

4 What we think we know and alternatives

Since low-scale gravity implies a new scale for physics, the search for non-perturbative gravity is likely to be enhanced as the LHC energy increases to the new scale. Since the production cross sections are anticipated to be large above the Planck scale, the usual view is that a search for non-perturbative gravity is enabled by the highest energies – not high luminosity. If the LHC energy is near the new gravity scale, we might expect an instant discovery at LHC turn-on at higher energies. Of course this can be wrong and black holes can be produced at some low rate at current energies, or decay to a different signature than that searched for so far. Two possibilities to reduce the cross section and make gravity states difficult to detect, even if we are above the new physics scale, are trap-surface calculations [10] and split-fermion models [11]. One of the only models that can predict new signatures, that I know of, is non-commutative geometry black hole models [12]. I will not discuss models that predict a stable remnant at the Planck scale.

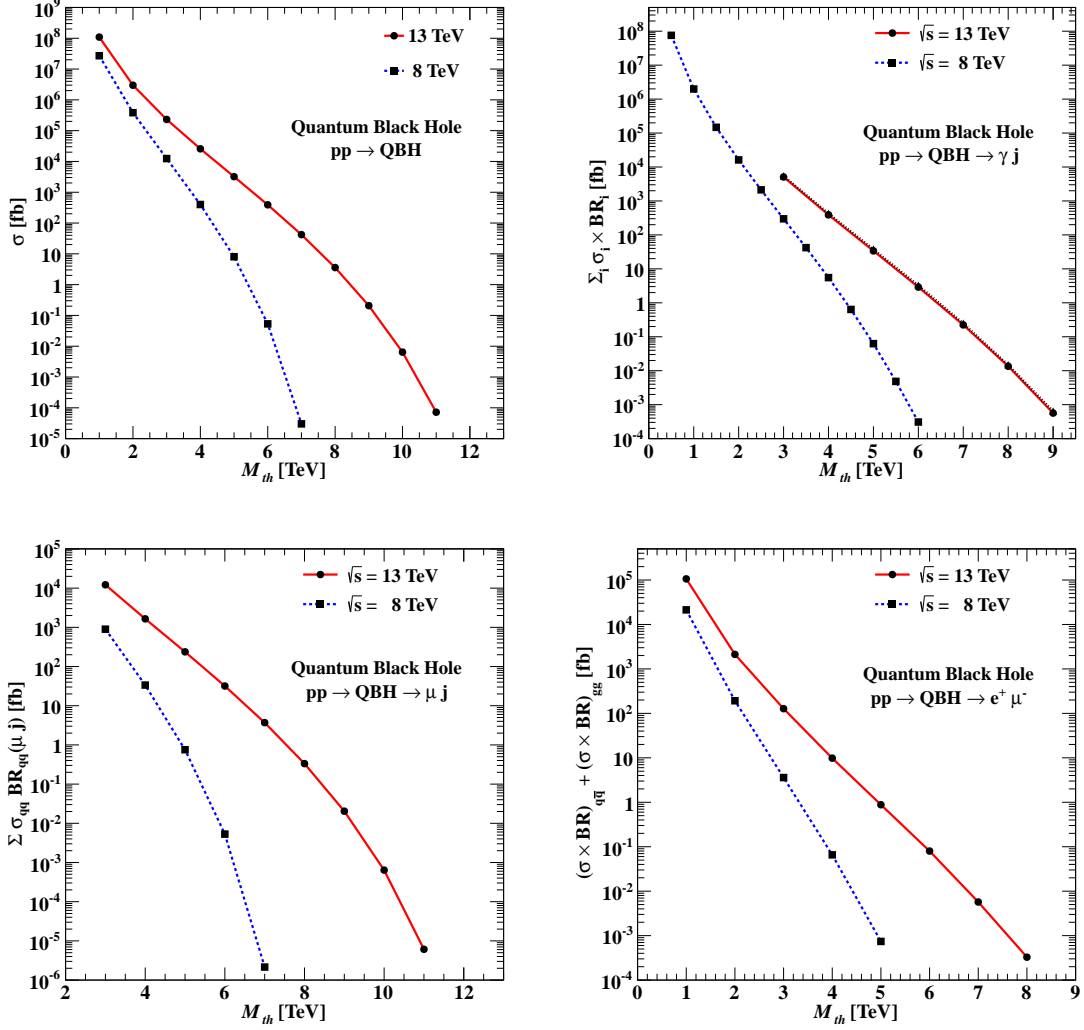


Figure 4: Cross section time branching fraction for different QBH channels at LHC proton–proton centre of mass energies of 8 TeV and 13 TeV: (top-left) inclusive, (top-right) γ +jet, (bottom-left) ℓ +jet, and (bottom-right) dilepton.

Typically a total inelastic classical cross section form $\sigma = \pi r_g^2$, where r_g is the gravity radius is used for the black hole parton–parton cross section. All the energy of the partons is assumed to go into producing the black hole. But this is unlikely as various GR calculations predict only a fraction of the energy in a particle–particle collision will be trapped behind the horizon formed. The excess energy “appears” as radiation. I will refer to this initial-state radiation as radiation that can be considered to occur before the black hole is formed, and balding radiation as radiation that can be considered to occur after black hole formation. In the former case, less energy is available for black hole formation and the cross section is reduced. Neither of these radiation processes is consider as Hawking radiation. Upper bounds on the amount of initial-state radiation for higher-dimension black holes have been calculated [42]. Figure 5 shows the case of applying the trapped surface cross section results from Ref. [42] to QBH production.

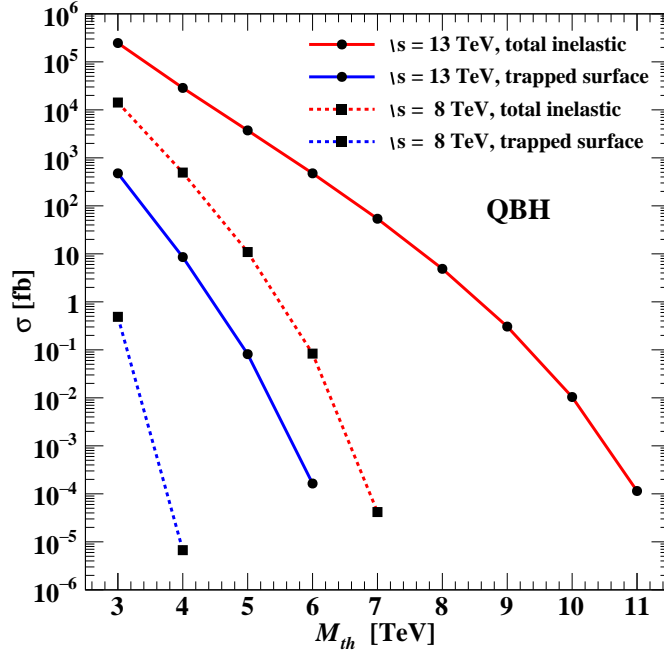


Figure 5: Comparison of total inelastic cross section and trapped surface cross section [42] applied to QBH production at 8 TeV and 13 TeV proton–proton centre of mass energy.

Split-fermion models are a mechanism for generating Yukawa hierarchies by displacing the standard model fermion fields in a high-dimensional space by localising them to different positions on a thick brane. The overlap of the fermion wave functions give the couplings. A set of spacings giving masses consistent with data has been determined in a two-dimensional split-fermion model [43]. One can embed black holes and string balls in split-fermion models. This can cause a reduction in cross section relative to the usual ADD case [44]. Split-fermion models have yet to be used to interpret results from the LHC experiments.

ADD-type black holes have been embedded into a non-commutative geometry [12]. It is hoped that some of the aspects of a theory of quantum gravity will be reflected in the model by including the non-commutative geometry. The matter distributions are smeared with a resolution given by the non-commutative scale. This introduces an extra parameter into the model: $\sqrt{\theta}$. A benefit is that the temperature is well behaved during Hawking evaporation all the way down to the Planck scale – unlike the semi-classical model in GR. Or in other words, the canonical ensemble treatment of entropy is valid for entire decay [45]. The gravitational radius has a non-zero minimum. This results in a remnant. But unlike most remnant models, the remnant mass is different from the Planck scale. The model exists and gives rather different phenomenological signatures than the usual models [15]. The main experimental differences include a large missing energy in events and a soft $\sum p_T$ spectrum of particles.

5 Discussion

For the model-independent analyses, upper limits on the fiducial cross section as a function of inclusive $\sum p_T$ are determined. There seems no good method for removing the model dependence and making the results generic. In an ideal world, it would be beneficial to have the model dependence removed from the model-independent limits. Especially for low-scale gravity in which the models are rather speculative.

Model-dependent limits are set in the two-dimensional parameter space of M_{th} and M_D . The other parameters are fixed and the result is called a model. The choice of which parameters to leave fixed and their values are somewhat arbitrary. For example, $g_s = 0.4$ is held constant when setting limits on string balls. The choice of g_s can case the search to be sensitive in the stringy, unitarity, or black hole regime of cross section depending on its value. Thus the limits may depend significantly on the choice of g_s . Lower mass limits are set on M_{th} as a function of the other parameters in the model. I remind the reader that M_{th} is not a physical parameter but a cut-off to parameterise the validity of the model. M_{th} can vary considerably over the range of M_D , and presumably over the possible range of other parameters that are held fixed at arbitrary values. At best, model-dependent limits allow a comparison of the sensitivity to different models relative to each other in a given analysis strategy, and a comparison of the sensitivity to the same model between analysis strategies. I see no physics reason for producing model-dependent limits.

In most cases, searches for thermal states are performed in the $\sum p_T$ variable. This variable is not directly related to the analytical form of the cross section. For the model-independent limits, it may be possible to obtain higher mass limits by using invariant mass rather than $\sum p_T$. It may even be possible with some additional work to perform the search in $\sum p_T$, but set the limits in mass. Cross section limits in mass would allow a direct use of the theory to determine the upper mass reach, and possibly limits on M_D . This is already done in the non-thermal limits which are preformed in mass.

The analyses in ATLAS dealing with thermal black hole searches do not consider missing transverse momentum. This seems puzzling since neutrinos give rise to missing momentum

and should be produced with equal, or one-half, the probability of charged leptons. If the production of charged leptons is significant enough to design a search based on them, the effect of missing energy from neutrinos should be of some significance in the analysis if not accounted for. In addition, in a model of low-scale quantum gravity it is hard to imagine that gravitons are not produced. Gravitons should give rise to missing energy, and their production may well be significant [46].

6 Summary

To date, the experiments at the LHC have published a total of 16 papers which search for non-perturbative gravity states. Based on lower limits on the Planck scale and an acceptable validity of the GR black hole model, these states have been ruled out at LHC energies of 13 – 14 TeV. By the same reasoning, string ball states are also likely to be ruled out, but there may be a small window of validity above 13 TeV.

Searches for non-thermal black holes allow a direct model-dependent limit of the mass. The dijet channel is very powerful and sets the most stringent limits on the low-scale gravity scale. It would be beneficial to use the dijet signature to interpret models that predict significantly lower cross sections than the usual models – like RS1 and trapped surface cross sections.

Low-scale gravity studies are expected to benefit more from an increase in LHC energy than luminosity. This expectation is based on the nominal models. Quantum gravity effects, or other unaccounted for effects, may cause cross sections to be lower than expected.

Prior to the turn-on of the LHC a large number of papers discussing low-scale gravity were written. The overwhelmingly majority used 1 TeV as the gravity scale. In spite of some shortcomings of the non-thermal state searches, combined with the limits on M_D from mono-jets, it is advisable to increase the gravity scale to at least 3 TeV in any future phenomenological studies. The predictions in proton–proton collisions will be less dramatic than those early papers of about 17 years ago.

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References

- [1] N. Arkani-Hamed, S. Dimopoulos, and G. Dvali, *The hierarchy problem and new dimensions at a millimeter*, Phys. Lett. B **429** (1998) 263–272, [arXiv:hep-ph/9803315 \[hep-ph\]](#).

- [2] I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos, and G. Dvali, *New dimensions at a millimeter to a Fermi and superstrings at a TeV*, Phys. Lett. B **436** (1998) 257–263, [arXiv:hep-ph/9804398](#) [hep-ph].
- [3] L. Randall and R. Sundrum, *A large mass hierarchy from a small extra dimension*, Phys. Rev. Lett. **83** (1999) 3370–3373, [arXiv:hep-ph/9905221](#) [hep-ph].
- [4] S. B. Giddings and S. D. Thomas, *High-energy colliders as black hole factories: The end of short distance physics*, Phys. Rev. D **65** (2002) 056010, [arXiv:hep-ph/0106219](#) [hep-ph].
- [5] S. Dimopoulos and G. L. Landsberg, *Black holes at the LHC*, Phys. Rev. Lett. **87** (2001) 161602, [arXiv:hep-ph/0106295](#) [hep-ph].
- [6] G. Dvali and M. Redi, *Black Hole Bound on the Number of Species and Quantum Gravity at LHC*, Phys. Rev. D **77** (2008) 045027, [arXiv:0710.4344](#) [hep-th].
- [7] S. W. Hawking, *Particle Creation by Black Holes*, Commun. Math. Phys. **43** (1975) 199–220.
- [8] S. Dimopoulos and R. Emparan, *String balls at the LHC and beyond*, Phys. Lett. B **526** (2002) 393–398, [arXiv:hep-ph/0108060](#) [hep-ph].
- [9] P. Meade and L. Randall, *Black Holes and Quantum Gravity at the LHC*, J. High Energy Phys. **0805** (2008) 003, [arXiv:0708.3017](#) [hep-ph].
- [10] D. M. Eardley and S. B. Giddings, *Classical black hole production in high-energy collisions*, Phys. Rev. D **66** (2002) 044011, [arXiv:gr-qc/0201034](#) [gr-qc].
- [11] N. Arkani-Hamed, Y. Grossman, and M. Schmaltz, *Split Fermions in Extra Dimensions and Exponentially Small Cross-Sections at Future Colliders*, Phys. Rev. D **61** (2000) 115004, [arXiv:hep-ph/9909411](#) [hep-ph].
- [12] T. G. Rizzo, *Noncommutative inspired black holes in extra dimensions*, J. High Energy Phys. **0609** (2006) 21, [arXiv:hep-ph/0606051](#) [hep-ph].
- [13] J. A. Frost, J. R. Gaunt, M. O. Sampaio, M. Casals, S. R. Dolan, et al., *Phenomenology of production and decay of spinning extra-dimensional black holes at hadron colliders*, J. High Energy Phys. **0910** (2009) 014, [arXiv:0904.0979](#) [hep-ph].
- [14] D. M. Gingrich and K. Martell, *Study of highly-excited string states at the Large Hadron Collider*, Phys. Rev. D **78** (2008) 115009, [arXiv:0808.2512](#) [hep-ph].
- [15] D. M. Gingrich, *Noncommutative geometry inspired black holes in higher dimensions at the LHC*, J. High Energy Phys. **1005** (2010) 022, [arXiv:1003.1798](#) [hep-ph].

- [16] D.-C. Dai, G. Starkman, D. Stojkovic, C. Issever, E. Rizvi, et al., *BlackMax: A black-hole event generator with rotation, recoil, split branes, and brane tension*, Phys. Rev. D **77** (2008) 076007, [arXiv:0711.3012 \[hep-ph\]](#).
- [17] D. M. Gingrich, *Monte Carlo event generator for black hole production and decay in proton-proton collisions*, Comput. Phys. Commun. **181** (2010) 1917–1924, [arXiv:0911.5370 \[hep-ph\]](#).
- [18] D. M. Gingrich, *Experimental limits on the fundamental Planck scale in large extra dimensions*, [arXiv:1210.5923 \[hep-ex\]](#).
- [19] CMS Collaboration, *Search for dark matter, extra dimensions, and unparticles in monojet events in proton-proton collisions at $\sqrt{s} = 8$ TeV*, Eur. Phys. J. C **75** (2015) 235, [arXiv:1408.3583 \[hep-ex\]](#).
- [20] ATLAS Collaboration, *Search for low-scale gravity signatures in multi-jet final states with the ATLAS detector at $\sqrt{s} = 8$ TeV*, J. High Energy Phys. **1507** (2015) 032, [arXiv:1503.08988 \[hep-ex\]](#).
- [21] CMS Collaboration, *Search for microscopic black hole signatures at the Large Hadron Collider*, Phys. Lett. B **697** (2011) 434–453, [arXiv:1012.3375 \[hep-ex\]](#).
- [22] CMS Collaboration, *Search for microscopic black holes in pp collisions at $\sqrt{s} = 7$ TeV*, J. High Energy Phys. **1204** (2012) 061, [arXiv:1202.6396 \[hep-ex\]](#).
- [23] CMS Collaboration, *Search for microscopic black holes in pp collisions at $\sqrt{s} = 8$ TeV*, J. High Energy Phys. **1307** (2013) 178, [arXiv:1303.5338 \[hep-ex\]](#).
- [24] ATLAS Collaboration, *Search for TeV-scale gravity signatures in final states with leptons and jets with the ATLAS detector at $\sqrt{s} = 7$ TeV*, Phys. Lett. B **716** (2012) 122–141, [arXiv:1204.4646 \[hep-ex\]](#).
- [25] ATLAS Collaboration, *Search for microscopic black holes and string balls in final states with leptons and jets with the ATLAS detector at $\sqrt{s} = 8$ TeV*, J. High Energy Phys. **1408** (2014) 103, [arXiv:1405.4254 \[hep-ex\]](#).
- [26] ATLAS Collaboration, *Search for strong gravity signatures in same-sign dimuon final states using the ATLAS detector at the LHC*, Phys. Lett. B **709** (2012) 322–340, [arXiv:1111.0080 \[hep-ex\]](#).
- [27] ATLAS Collaboration, *Search for microscopic black holes in a like-sign dimuon final state using large track multiplicity with the ATLAS detector*, Phys. Rev. D **88** (2013) 072001, [arXiv:1308.4075 \[hep-ex\]](#).
- [28] ATLAS Collaboration, *Search for new phenomena in the dijet mass distribution using $p - p$ collision data at $\sqrt{s} = 8$ TeV with the ATLAS detector*, Phys. Rev. D **91** (2015) 052007, [arXiv:1407.1376 \[hep-ex\]](#).

- [29] CMS Collaboration, *Search for narrow resonances and quantum black holes in inclusive and b-tagged dijet mass spectra from pp collisions at $\sqrt{s} = 7$ TeV*, J. High Energy Phys. **1301** (2013) 013, [arXiv:1210.2387 \[hep-ex\]](#).
- [30] CMS Collaboration, *Search for resonances and quantum black holes using dijet mass spectra in proton-proton collisions at $\sqrt{s} = 8$ TeV*, Phys. Rev. D **91** (2015) 052009, [arXiv:1501.04198 \[hep-ex\]](#).
- [31] ATLAS Collaboration, *Search for new phenomena in photon+jet events collected in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, Phys. Lett. B **728** (2014) 562–578, [arXiv:1309.3230 \[hep-ex\]](#).
- [32] ATLAS Collaboration, *Search for Quantum Black Hole Production in High-Invariant-Mass Lepton+Jet Final States Using pp Collisions at $\sqrt{s} = 8$ TeV and the ATLAS Detector*, Phys. Rev. Lett. **112** (2014) 091804, [arXiv:1311.2006 \[hep-ex\]](#).
- [33] ATLAS Collaboration, *Search for high-mass dilepton resonances in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, Phys. Rev. D **90** (2014) 052005, [arXiv:1405.4123 \[hep-ex\]](#).
- [34] ATLAS Collaboration, *Search for New Physics in Dijet Mass and Angular Distributions in pp Collisions at $\sqrt{s} = 7$ TeV Measured with the ATLAS Detector*, New J. Phys. **13** (2011) 053044, [arXiv:1103.3864 \[hep-ex\]](#).
- [35] ATLAS Collaboration, *ATLAS search for new phenomena in dijet mass and angular distributions using pp collisions at $\sqrt{s} = 7$ TeV*, J. High Energy Phys. **1301** (2013) 029, [arXiv:1210.1718 \[hep-ex\]](#).
- [36] S. C. Park, *Critical comment on the recent microscopic black hole search at the LHC*, Phys. Lett. B **701** (2011) 587–590, [arXiv:1104.5129 \[hep-ph\]](#).
- [37] ATLAS Collaboration, *Search for strong gravity in jet final states produced in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC*, ATLAS-CONF-2015-043 (2015) 26. <http://cds.cern.ch/record/2048117>.
- [38] ATLAS Collaboration, *Search for TeV-scale gravity signatures in high-mass final states with leptons and jets with the ATLAS detector at $\sqrt{s} = 13$ TeV*, ATLAS-CONF-2015-046 (2015) 26. <http://cds.cern.ch/record/2052584>.
- [39] X. Calmet, W. Gong, and S. D. H. Hsu, *Colorful quantum black holes at the LHC*, Phys. Lett. B **668** (2008) 20–23, [arXiv:0806.4605 \[hep-th\]](#).
- [40] D. M. Gingrich, *Quantum black holes with charge, colour, and spin at the LHC*, J. Phys. G **37** (2010) 105008, [arXiv:0912.0826 \[hep-ph\]](#).

- [41] ATLAS Collaboration, *Search for New Phenomena in Dijet Mass and Angular Distributions with the ATLAS Detector at $\sqrt{s} = 13$ TeV*, ATLAS-CONF-2015-042 (2015) 26. <http://cds.cern.ch/record/2048113>.
- [42] H. Yoshino and V. S. Rychkov, *Improved analysis of black hole formation in high-energy particle collisions*, Phys. Rev. D **71** (2005) 104028, [arXiv:hep-th/0503171](#) [hep-th].
- [43] G. C. Branco, A. de Gouvea, and M. N. Rebelo, *Split fermions in extra dimensions and CP violation*, Phys. Lett. B **506** (2001) 115–122, [arXiv:hep-ph/0012289](#) [hep-ph].
- [44] S. Abdolrahimi and C. Tzounis, *Production of black holes and string balls in a two-dimensional split-fermion model*, J. High Energy Phys. **1409** (2014) 061, [arXiv:1407.0587](#) [hep-ph].
- [45] D. M. Gingrich and K. Martell, *Microcanonical treatment of black hole decay at the Large Hadron Collider*, J. Phys. G: Nucl. Part. Phys. **35** (2008) 035001, [arXiv:0708.0647](#) [hep-ph].
- [46] D. M. Gingrich, *Missing energy in black hole production and decay at the Large Hadron Collider*, J. High Energy Phys. **11** (2007) 064, [arXiv:0706.0623](#) [hep-ph].